Shockwave and Muzzle Blast Classification via Joint Time Frequency and Wavelet Analysis

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ABSTRACT

This paper will apply various joint time-frequency (JTF) and wavelet techniques to extract features from shockwave and muzzle blast signatures for the purpose of classification. The techniques used will include short-time Fourier transform (STFT), Smoothed Pseudo Wigner-Ville distribution (SPWVD) and wavelet multi-scale analysis. A projectile's trajectory can be estimated by measuring the arrival times of the acoustic energy at several locations in space. In the case of a supersonic projectile fired from a gun, both the acoustic shockwave and muzzle blast may be observed. For acoustic sensor systems attempting to determine a projectile's trajectory, the challenge is to first, correctly classify the transient signal as either a shockwave or a muzzle blast and then, calculate the direction-of-arrival via appropriate arrival times across a sensor array. This can be extremely challenging when the shockwave has lost substantial high frequency content. The change in spectral characteristics can stem from propagation over a long distance, propagation over snow covered terrain or arriving from a non-perfect reflector. An incorrect classification will result in large estimation errors of the projectile's trajectory. Experimental results are presented for proper classification over various miss distances from the sensors for all of the above techniques mentioned.

Introduction

Acoustic systems, which seek to exploit energy produced by supersonic projectiles, must correctly estimate the origin of the energy prior to processing. The supersonic projectile produces acoustic energy via a shock wave created by projectile motion and muzzle blast created at projectile launch. Proper discrimination between these two arrival energies at an acoustic system must be achieved if an estimation of the projectiles trajectory is desired. This stems from the propagation pattern of the two different energies. The muzzle blast energy will appear as a far field plane wave originating from the gun while the shock wave will propagate in the form of an acoustic cone trailing the projectile with angle $\theta = \arcsin(1/M)$, where M is the Mach number [1]. For an acoustic system that incorrectly classifies an acoustic arrival of a shock wave

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as a muzzle blast, the estimate of shot origin will be perpendicular to the shock cone incorrectly estimating the trajectory of the projectile.

The discrimination process is generally trivial in the case of ideal shock wave and muzzle blast arrival energies as the shock wave duration time is in the microsecond range while the muzzle blast duration is on the order of milliseconds. Under general conditions the shock wave spectral characteristics are greatly affected by propagation and can be severely attenuated over snow covered terrain. Also, many practical systems may have insufficient bandwidth to preserve rise time characteristics of the shock wave. Muzzle blast signatures can also be affected by multi-path situations producing apparently faster rise-times than anticipated.

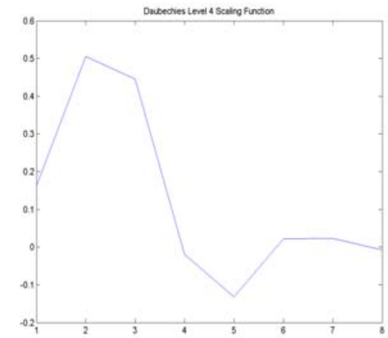
Theory

The acoustic energy produced by a super-sonic projectile will take on two forms, shockwave and muzzle blast. The energies produced by these two sources have differing durations, rise-times and arrival times relative to an arbitrary observer. These time and frequency dependent characteristic makes the event ideal to analyze with modern Joint Time-Frequency (JTF) techniques. In this paper three such JTF techniques are used to discriminate between such shockwave and muzzle blast events. The motivation for evaluating several techniques is to characterize performance vs. calculation complexity. The three techniques used in this paper are the Short-Time Fourier Transform (STFT) with results presented as spectrograms. The Discrete Wavelet Transform (DWT) is preformed with results presented as scalograms and the final technique used is the Smoothed Wigner-Ville Distribution (SWVD). All of the techniques used in this paper are classic JTF techniques and are covered in texts such as Ref. [2].

The STFT is perhaps the simplest and most commonly used JTF technique employed in general signal processing. The STFT results are easy to interpret, and generally characterize a signals frequency content over time. The largest drawback to this approach is that resolution obtainable in both the frequency and time domain are related and drive in opposite directions. Restated, better time resolution will produce poorer frequency resolution and vise-versa. The results of the STFT are generally squared to produce a Spectrogram which represents the signals power distribution over time and frequency. The equation defining the spectrogram for a given signal s(t) is:

$$Spectrogram(t,w) = \left(STFT(t,w)\right)^2 = \left[\left(\int s(\beta)w(\beta - t)e^{-jwt}\,d\beta\right)\right]^2$$

The next technique used is the DWT. This technique is attractive for two main reasons. First the DWT can be implemented as a successive bank of digital filters, which is a highly efficient process to implement. A second key feature of the DWT is that the time frequency resolutions vary over the JTF space. At higher frequencies you have better time resolution with reduced frequency resolution while at low frequencies you have better frequency resolution with reduced time resolution. This varying time resolution is important for the shockwave and muzzle blast data which both have sharp initial rise times but radically different durations. The DWT preserves the time location of the initial singularity allowing correct measurements of event onsets for both classes of signals[2]. The specific wavelet used in the analysis is a Daubechies



Level 4 wavelet and its corresponding smoothing function is shown in the adjoining figure. For the purposes of this paper, the specific wavelet was chosen empirically by evaluating the DWT performance in characterizing both shockwave and muzzle blast waveforms.

The final JTF technique applied is the calculation of the SWVD. A key reason for using the SWVD is that it clearly shows a signals frequency changes over time as compared with the STFT. The application of this technique to muzzle blast and shockwaves was investigated by others [3] but not it contrast to various JTF techniques. The SWVD is however very compute intensive for long duration signals. While the SWVD offers better resolution performance than the STFT it does suffer from cross-term interference patterns which can make the spectrum difficult to interpret. While the smoothing function reduces the cross-term effect excessive smoothing reduces the SWVD to a STFT under specific conditions negating any benefits. The equation defining the SWVD follow with W(t) representing the smoothing function and the star representing conjugation:

$$\widetilde{W}_f(x,t) = 2\int_{-\infty}^{+\infty} f(\tau+\tau')f(\tau-\tau')\,w_f(\tau')\,w_f^{*}(-\tau')\,e^{-2ix\tau'}\,d\tau'$$

Experimental and Simulated Data

For evaluation purposes both experimental and simulated data was analyzed with the three techniques previously described. The experimental shockwave and muzzle blast data was collected for a 7.62 mm weapon. The collection point for the acoustic data was 55 yards downrange from the shooter and at a height of approximately 2 feet off the ground. The collection equipment consisted of a B&K microphone, B&K amplifier and a 16-bit Sigma-Delta data acquisition card. The data was collected at a sample rate of 40 KHz. Data was collected for miss distances of 1 and 25 meters, defined as closest point of bullet trajectory to collection microphone. A total of 17 test signatures were used as a baseline data set for evaluation purposes and in shown in Figure below.

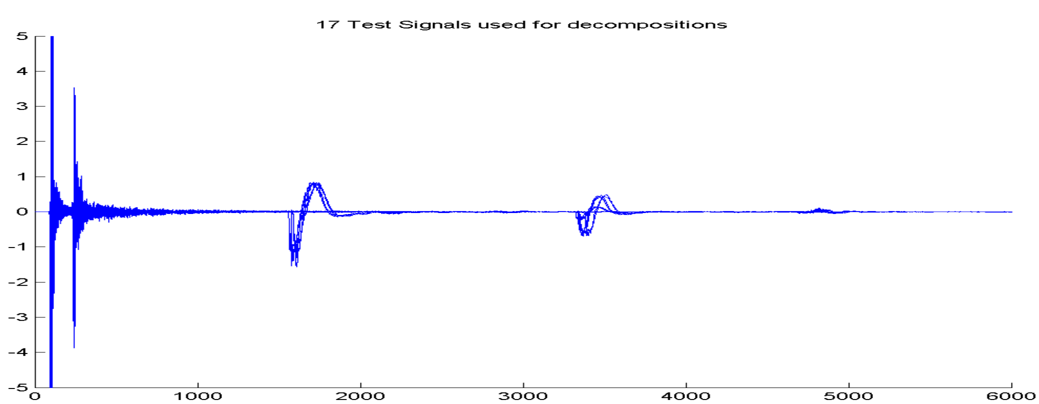


Figure 1: Test Signals Used

Simulated data was also used to provide a challenge data set to evaluated the various processing methods under difficult conditions. The two simulated conditions were the presence of a helicopter as an interference source and a severe echo condition in which a shockwave and muzzle blast signature overlay. These two simulated waveforms were created by simply scaling and adding live acoustic signatures which were collected independently. The simulated wave forms appear in the following Figures.

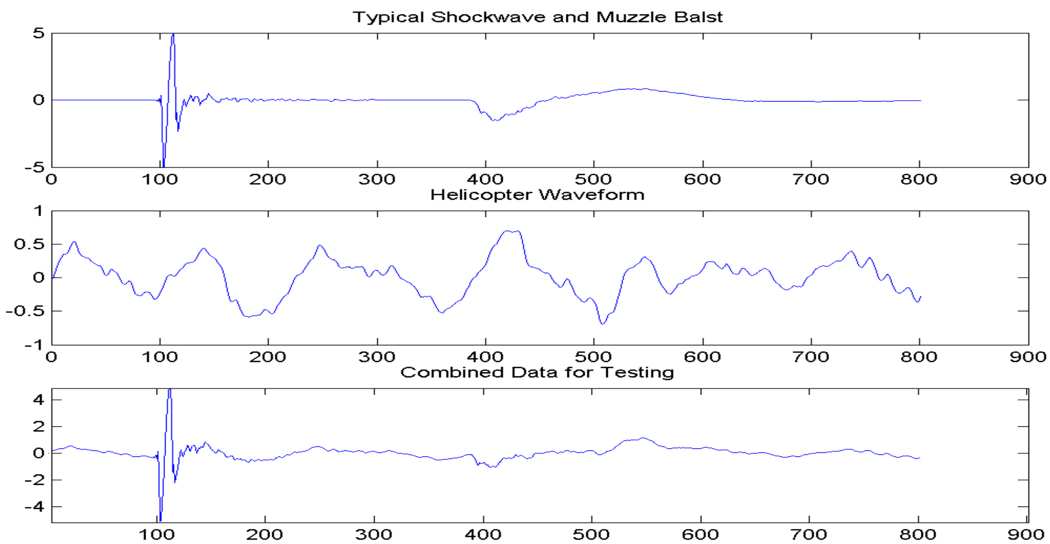


Figure 2: Simulated Helicopter Interference

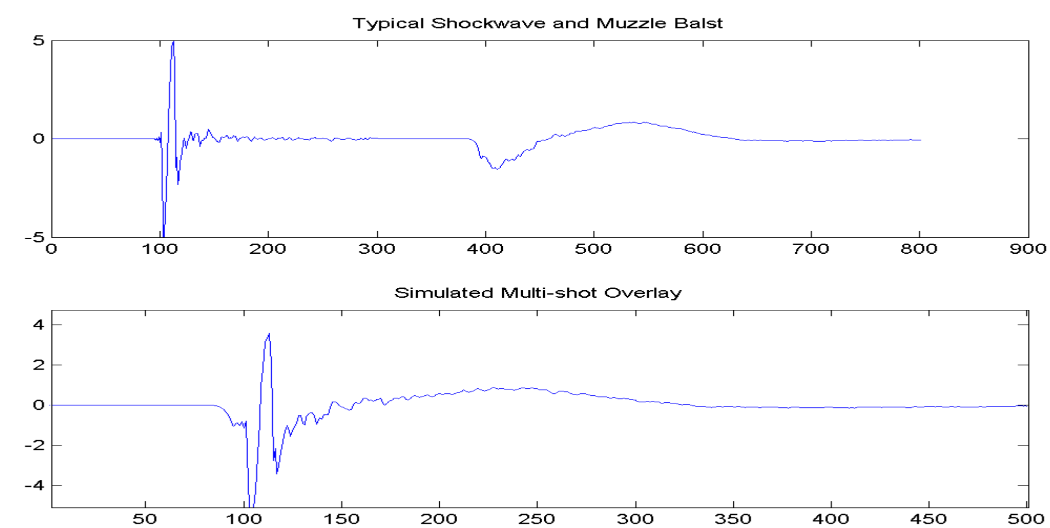


Figure 3: Simulated Echo Condition

Processed Results

All processed results shown in this paper were generated using MATLAB. The STFT is included in the Signal Processing Toolbox. The DWT routines are included Wavelet Toolbox. The SWVD algorithm used was from an open source Joint Time Frequency Toolbox developed by the French CNRS (Centre National de la Recherche Scientifique) and available at http://www-isis.enst.fr/Applications/tftb/iutsn.univ-nantes.fr/auger/.

STFT

In this section 4 signatures were processed via the STFT technique. For all 4 cases the Spectrogram was computed with a 128 pt FFT, 50% Overlap and a Hanning window was used. Figure 4 shows the Spectrogram results for a typical shockwave and muzzle blast signature. Note the two classes of signatures are easily discernable as the shockwave has broad energy content (above 1000 Hz) and short time of duration. While the muzzle blast has predominant energy content below 500Hz and a duration of several milliseconds. While this technique shows how easy the shockwave and muzzle blast signals may separate, the features of the shockwave are greatly distorted in time. The actual duration of the shockwave is on the order of .375 mSec but appears to last several mSec in the resulting spectrogram. This is a simple effect of the window size chosen and the limitation that time vs. frequency resolution must be traded off.

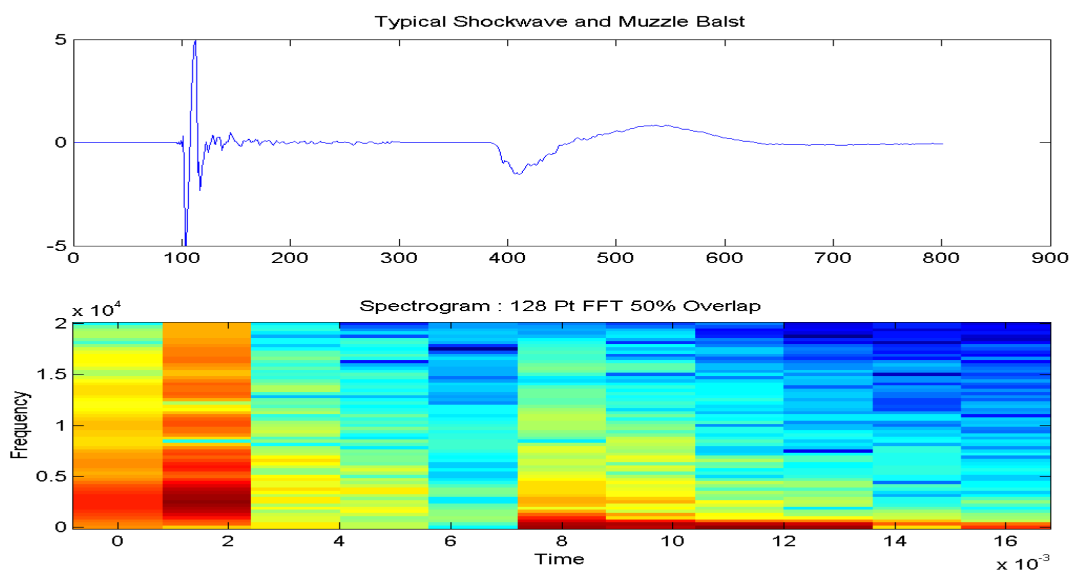


Figure 4

Figure 5 shows the spectrogram results for the simulated helicopter and shot overlay case. Note the shockwave is clearly discernable, but still has features distorted as before. The muzzle blast energy is lost in the helicopter background noise, this is primarily due to the similar frequency content and low signal to noise. While this is a challenging data set, close examination of the time waveform reveals that the discontinuity around sample 400 is detectable as a muzzle ballast feature but is lost due to the inherent averaging of the FFT.

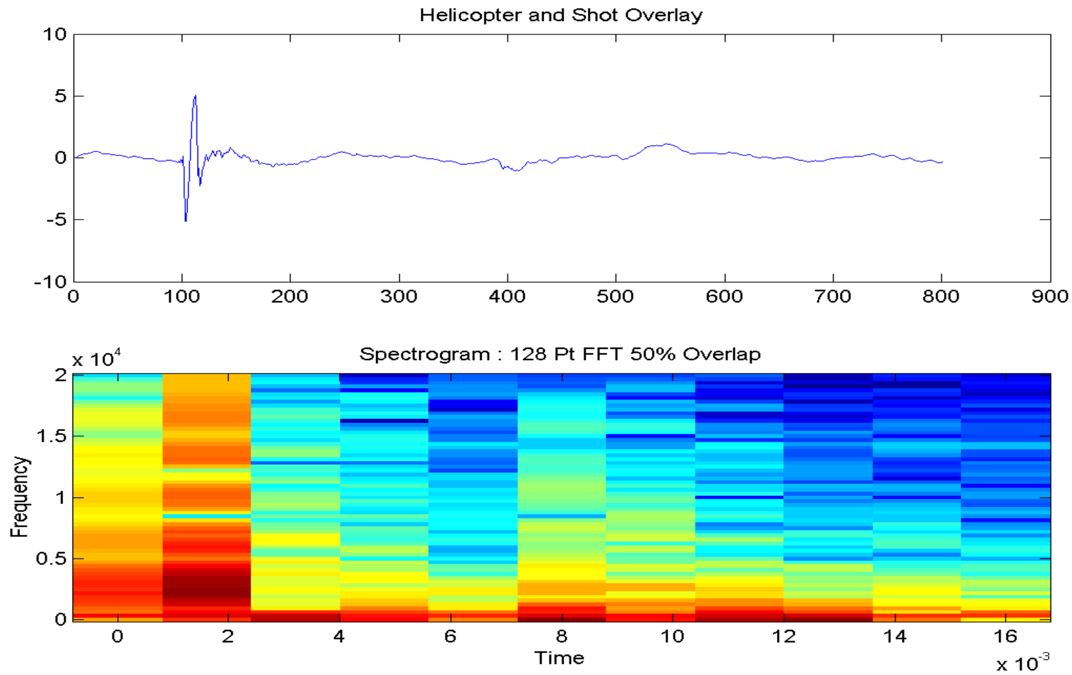


Figure 5

Figure 6 shows the spectrogram for the Muzzle and Crack overlay case which simulates a high echo environment. The spectrogram does show the presence of energy both above and below 1Khz, indicating its more than a shockwave, but may be difficult separating from any other transient forms of data.

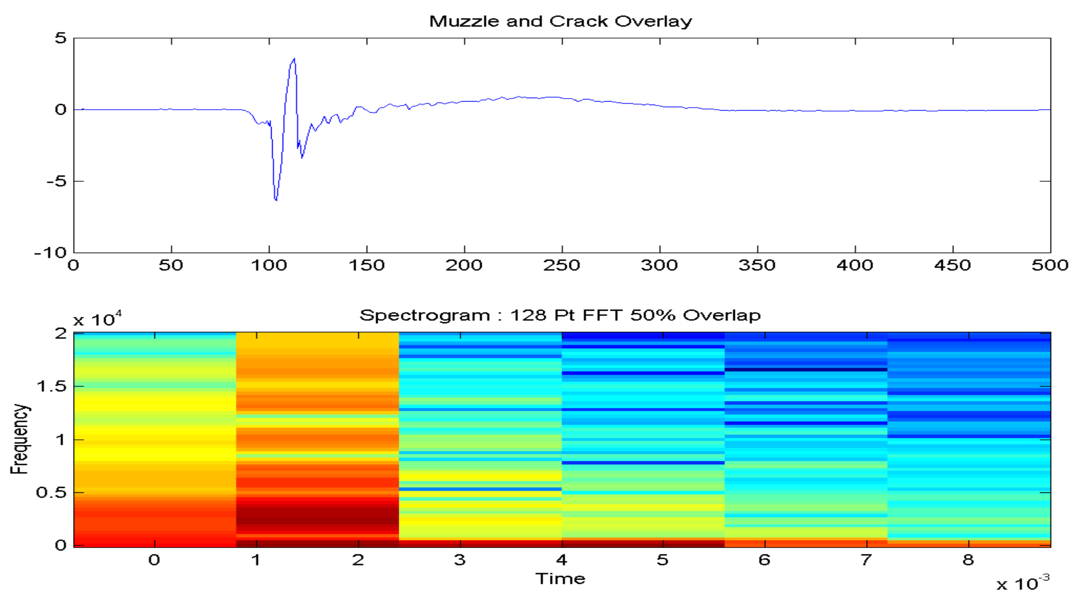


Figure 6

Figure 7 is the last set of data processed with the STFT technique. This data was collected in a highly reverberant environment which is typical in an urban setting. The multiple echoes are clearly visible for the shockwaves throughout the time spectrum. The muzzle blast energy which occurs around sample 6000 is barely visible in the time waveform and is itself followed by many echoes. The echoes here create a background acoustic energy which is similar in band to the lower frequency muzzle blast energy and effectively masks the muzzle blast in the spectrogram. The masking is a direct effect of the averaging and poor time isolation of the events.

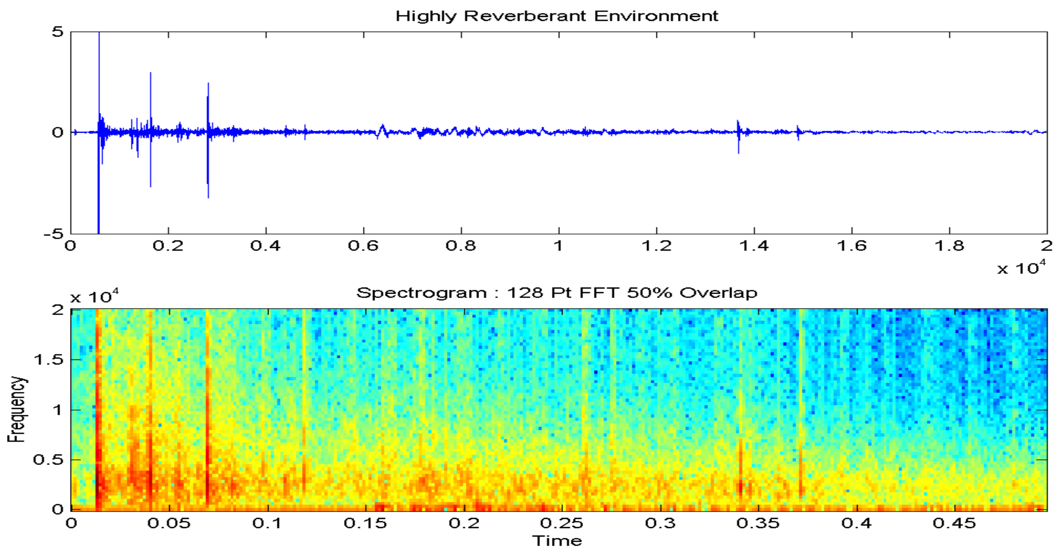


Figure 7

Wavelet Based

All of the figures in this section show the results of the DWT transform over the first 8 scales. The specific wavelet used was a Daubechies level 4 wavelet. The results are in the form of a scalogram, which is a plot of the wavelet detail coefficients as a function of time and scale. For alignment purposes the coefficients at higher scales are repeated, which is required due to the reduce time resolution (and hence fewer coefficients). A second step taken to ensure time alignment with respect to vertical slices was to remove the effective group delay introduced at each successive wavelet decomposition level. Figure 8 shows the results of the DWT procedure for the typical signature case. Note that the shockwave and muzzle blast separate cleanly in the scale dimension. This is due to the impulsive nature and short cycle time of the shockwave while the muzzle blast has an initial transient but decays over a much longer time window. It is also useful to note the time of occurrence of the two events is accurately indicated in the scalogram. The DWT preserves the initial singularity that both the shockwave and muzzle blast have, marking the onset of the energy at the different scales. Figure 9 applies a simple global threshold to the scalogram in Figure 8 to highlight the critical features. This simple technique is generally used for compression techniques to select high value coefficients and preserve the majority of the signal's energy while minimizing the information required to do so. This same procedure effectively selects the dominant features between the two classes of signatures in this case.

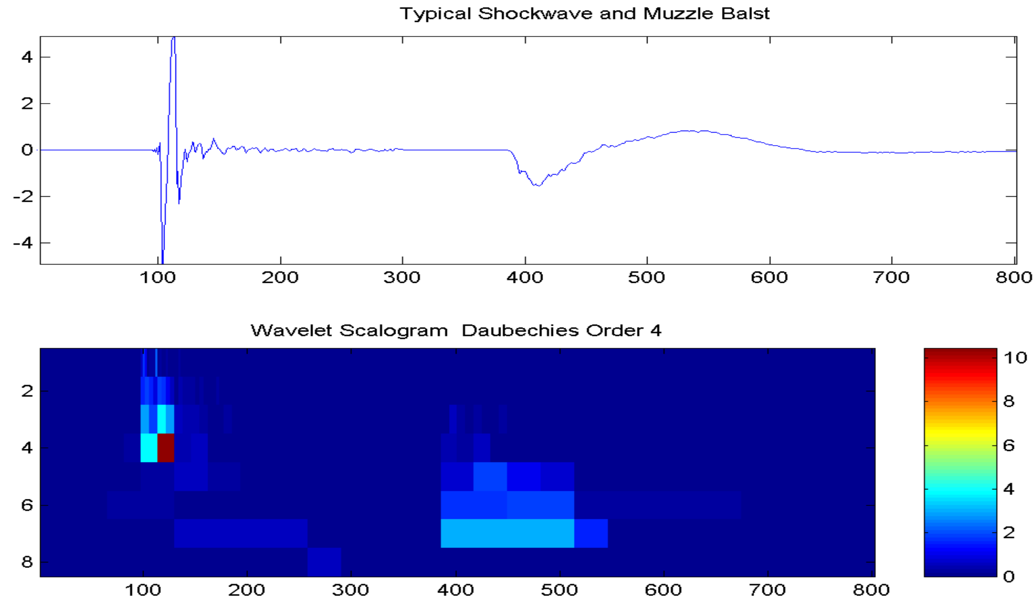


Figure 8

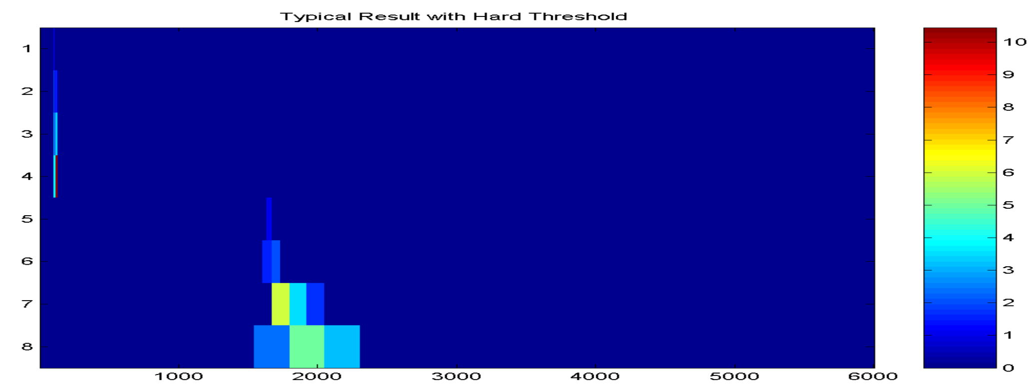


Figure 9

Figure 10 shows the DWT results for the helicopter and shot overlay data. Note that the shockwave is clearly detected in the first several scales but the muzzle blast is lost in the higher scales. This performance is as expected since the helicopter energy is on the same scale as the muzzle blast. This case is severe in that the signal power ratio between the muzzle and the helicopter is about equal.

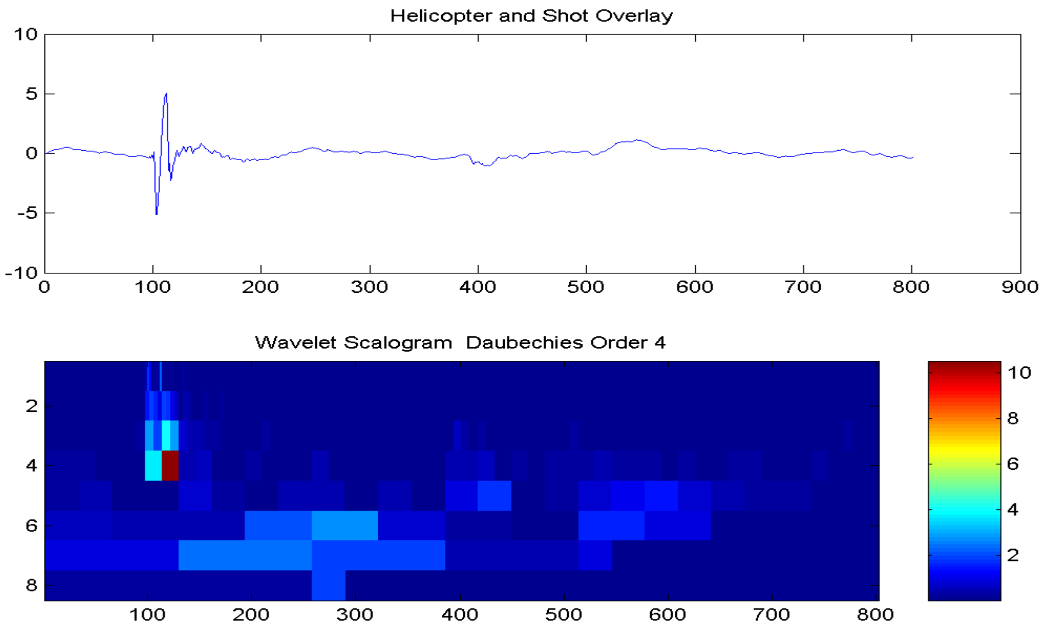


Figure 10

Figure 11 shows the DWT results for the shockwave muzzle blast overlay. The results do show energy at both low and high scales indicating the potential presence of both classes of energy.

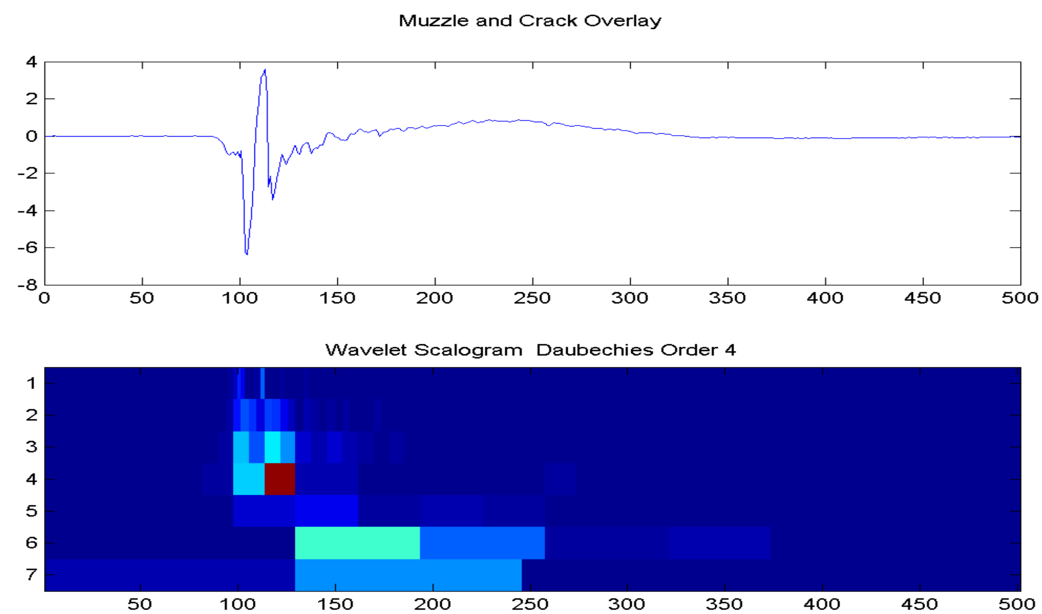


Figure 11

Figure 12 shows the DWT performance in the highly reverberant environment. Note that the initial shockwave and subsequent echoes are clearly marked in scale and time of occurrence. The fine time resolution of the lower scales allows the individual echoes to be located and counted. In the case of the higher scales the initial muzzle blast is detectable at the proper time location (Approx sample 6500) but all of the echoes smear together. This is explained as the arrival times between echo sources is approaching the time duration of the muzzle blast. While this stretches the apparent duration of the event the arrival time of the initial blast is accurate.

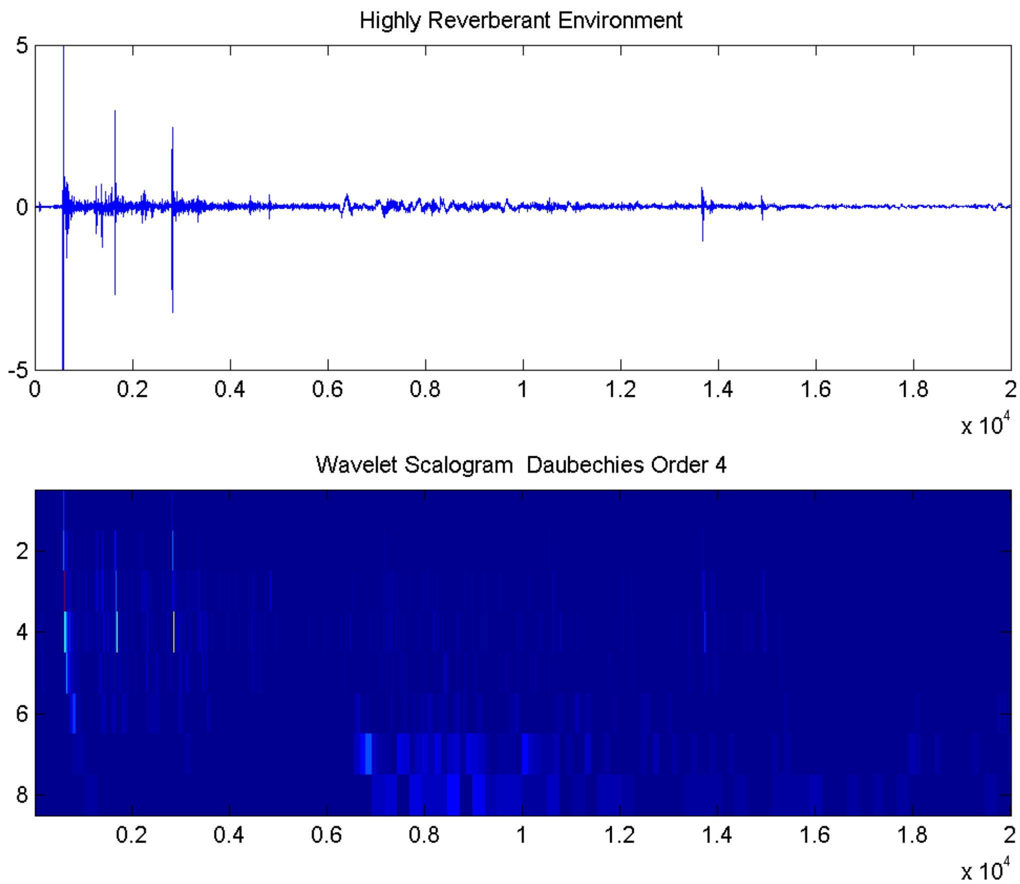


Figure 12

Figure 13 runs the DWT against the 17 test data files presented earlier. This was done to show consistency with the method. Note that in most of the cases the shockwave and muzzle blasts clearly separate in scale. There are some cases were the shockwaves appear to have energy at low and high scale which is contrary to their ideal fundamental shape. That is, these signals should be a single cycle waveform at a relatively high frequency. I believe that the data which shows energy across high scales as well may be due to the effect of a large miss distance. Under this condition the second shockwave signature from the ground reflection is very close in time to the primary arrival. This may be creating an envelope effect in which the total shockwave duration appears elongated to the presence of an extra cycle with no isolation between the events.

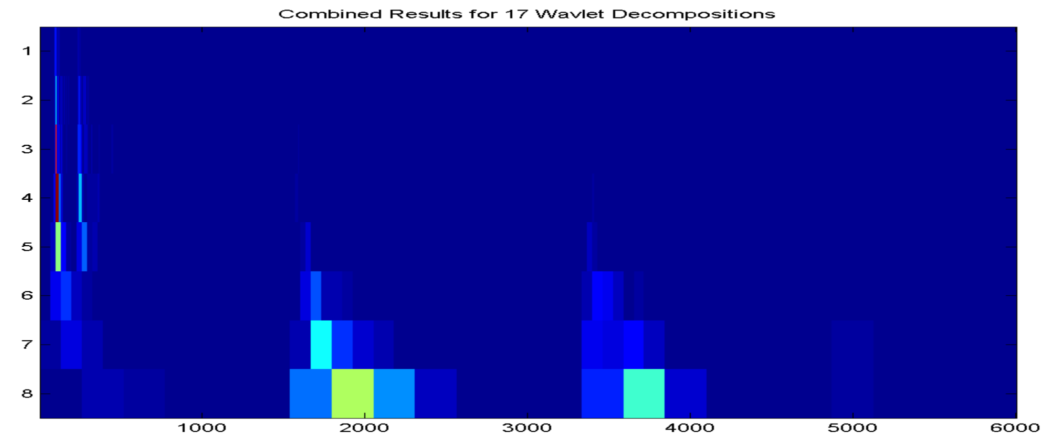


Figure 13

Smoothed-Pseudo Wigner-Ville time-frequency distribution

The last section shows the results from processing the test data to compute the SWVD. Figure 14 shows the results for the typical signature. The two classes are clearly separated in time and frequency. Also note that the results show some structure to the JTF representation which may be exploitable. The most notable feature is the specific shapes to the individual cases.

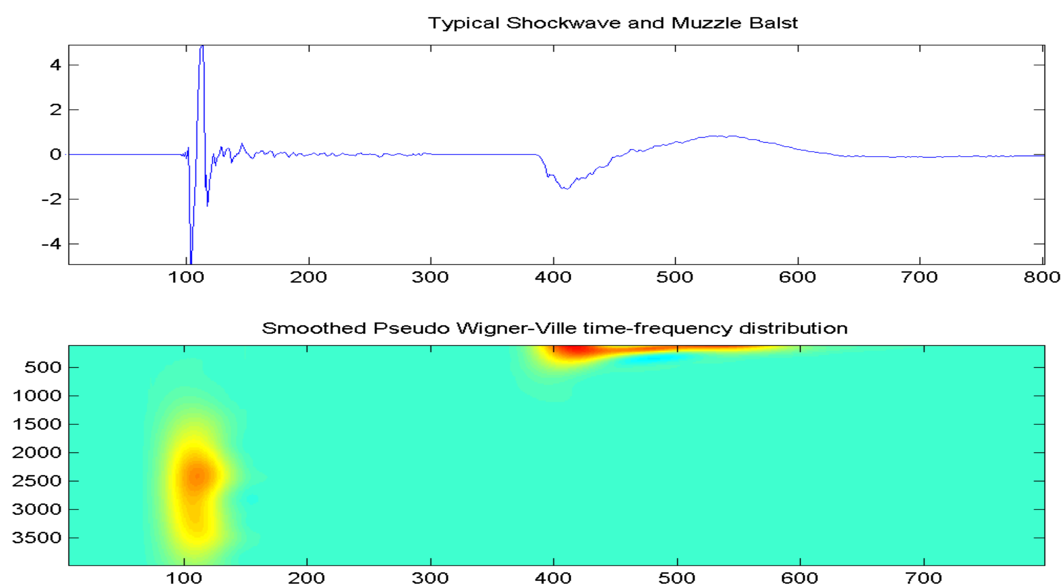


Figure 14

Figure 15 shows the SWVD results for the combined helicopter and shot overlay data. Note the cross term interference patterns around the shockwave. This interference pattern can be one of the challenges with using the SWVD for classification in that the features are effected by the specific interferer. The muzzle blast is not isolatable with this technique for the same reasons stated before.

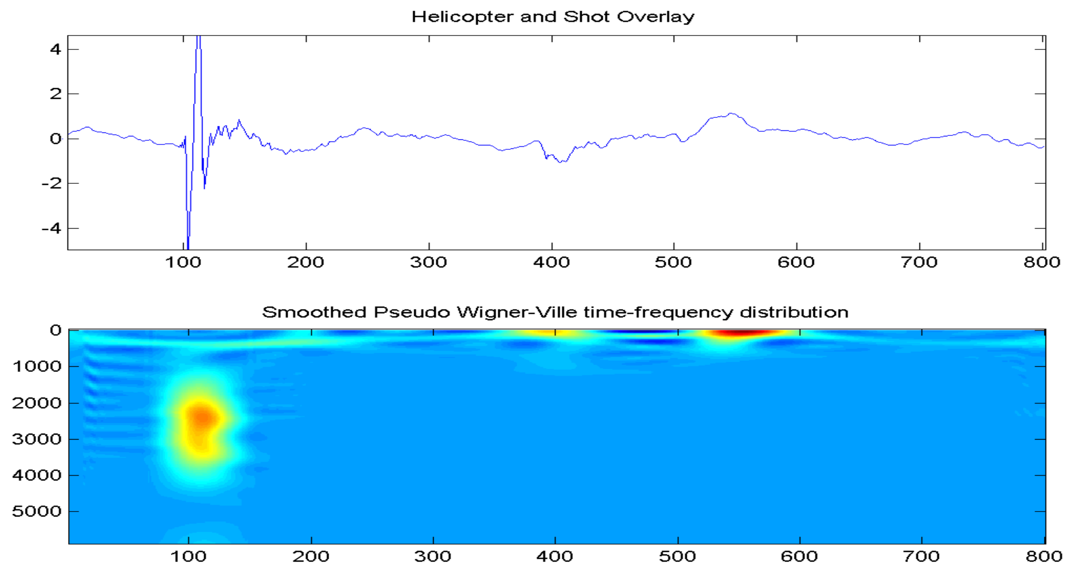


Figure 15

Figure 16 shows the results for the shockwave and muzzle overlay signal. The SWVD does an excellent job of isolating the two events. It preserves the arrival times and general signature shape of the JTF distribution.

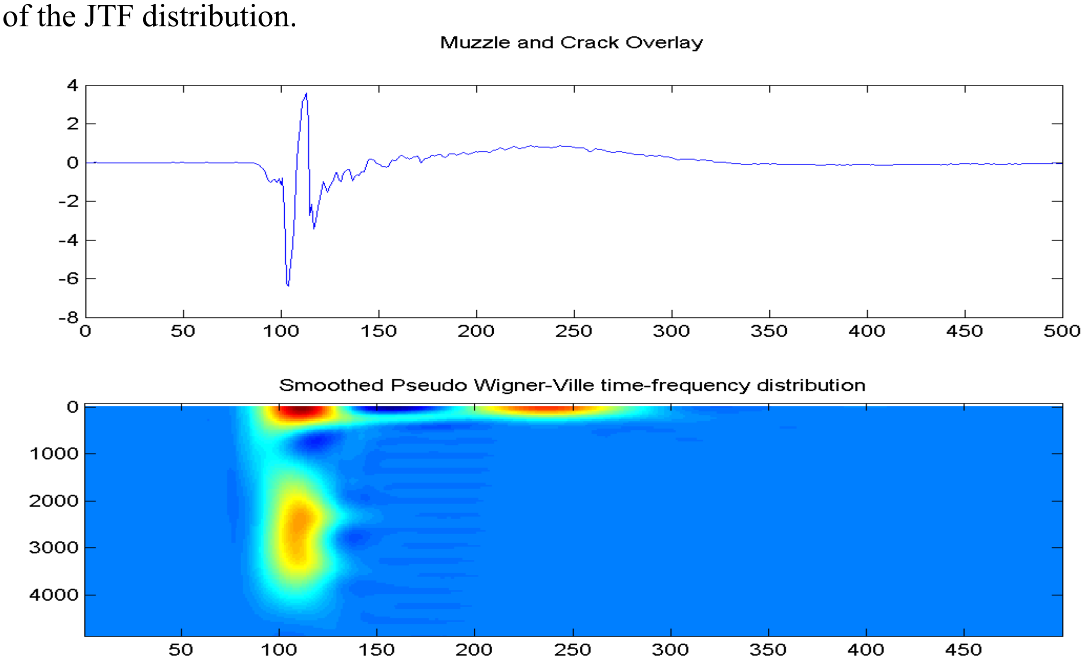


Figure 16

Conclusions

The three JTF techniques applied to the specific shockwave and muzzle blast classification problem all show merit but no single method appears optimum. The STFT method is the most classic and well understood technique but has very poor ability to accurately resolve transient event onset times while simultaneously resolving frequency content. The DFT performs well with respect to resolving onset times and isolating frequency content but still suffers when similar signals are interference sources. This was clearly demonstrated in the simulated helicopter data. The SWVD technique shows promise but is costly to implement in terms of require processing power. This may limit its application to many realizable systems. Beyond the calculation complexity, the cross-term interference patterns which plague the SWVD must be fully investigated for know interference sources.

For systems which must balance performance with implementation complexity, the DWT appears to be the best of the three candidate JTF techniques evaluated in this paper. Further study needs to be done to quantify the DFT processing approach under various environmental conditions as the acoustic shockwave and muzzle blast features are highly affected by atmospheric propagation. The inclusion of a large set of know interferers must also be used before any final recommendations of which method is sufficient to meet a required level of performance.

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